Supplementary Information

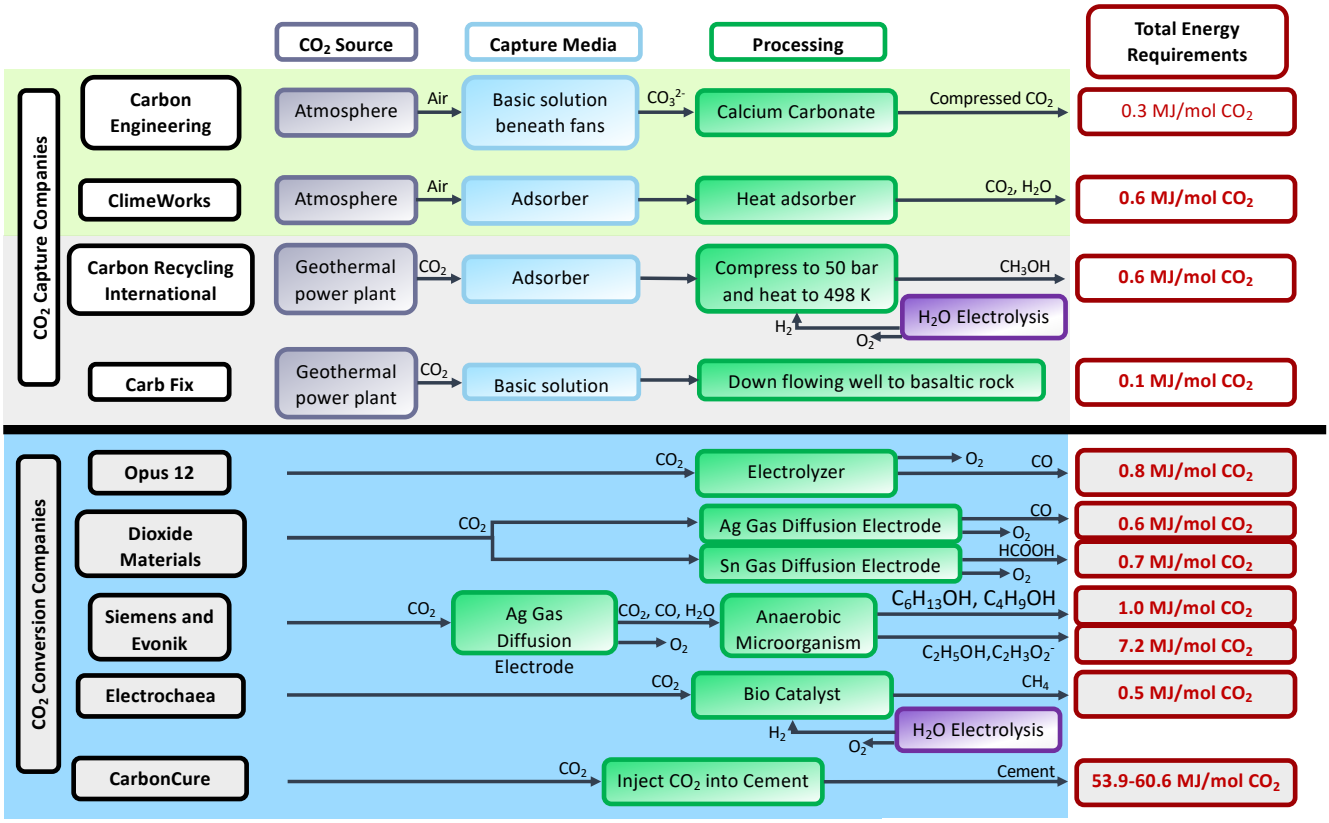
Bicarbonate or Carbonate Processes for Coupling Carbon Dioxide Capture and Electrochemical Conversion

*Alex J. Welch,[1,2] Emily Dunn,[1,2] Joseph S. Duchene,[2,3] and Harry A. Atwater[1,2]**

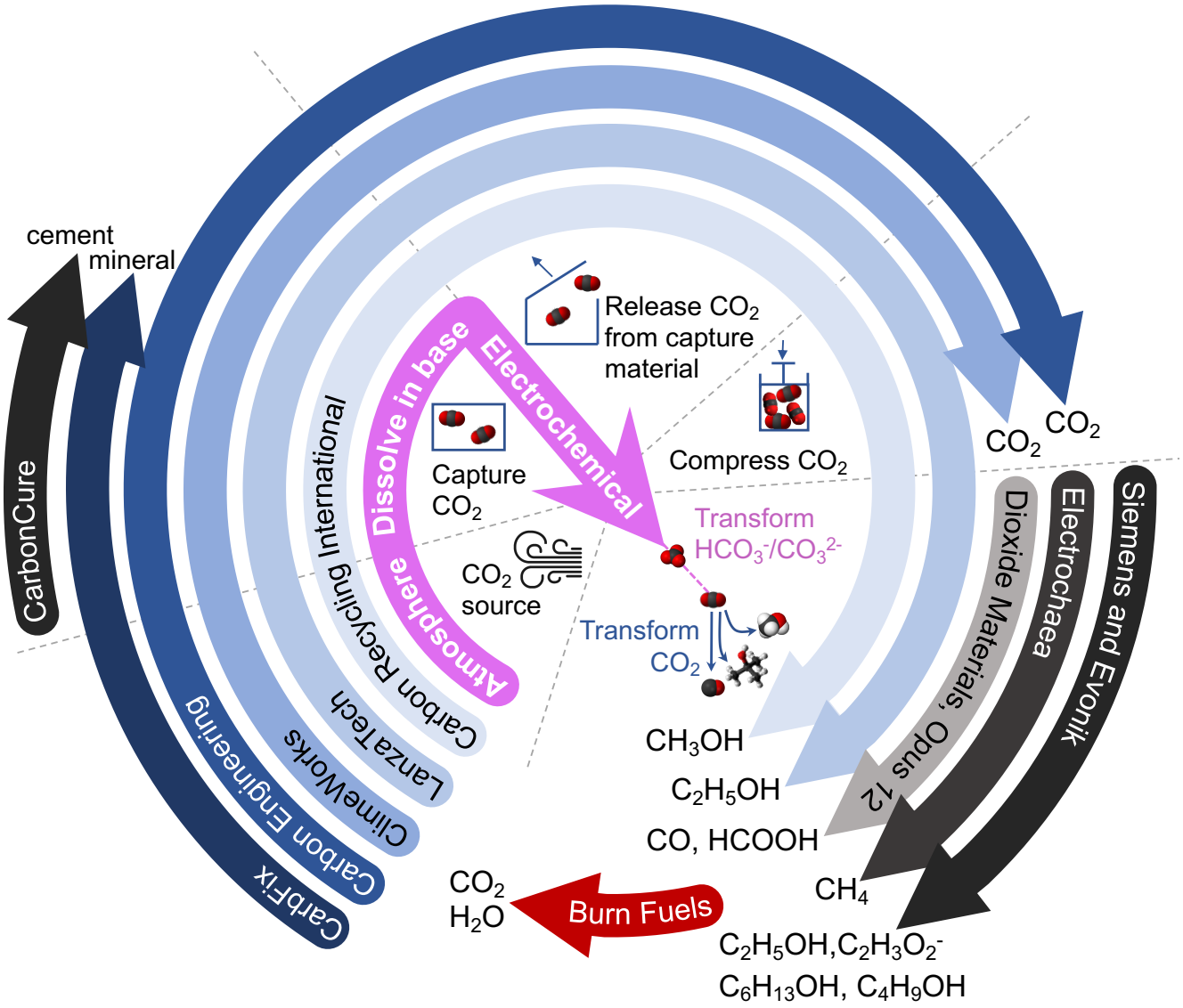
[1] Department of Applied Physics and Material Science, California Institute of Technology, Pasadena, CA 91125, USA.

[2] Joint Center for Artificial Photosynthesis, California Institute of Technology, Pasadena, CA 91125, USA.

[3] Department of Chemistry, University of Massachusetts Amherst, Amherst, MA, 01003, USA.



Supplementary Figure 1: Schematic representation of various pilot plants that capture CO_2 and/or transform it to either concentrated and pressurized CO_2 or to a value-added product. The companies in the light blue region capture CO_2 from the atmosphere. The companies in the mid-blue region capture CO_2 from concentrated sources. The companies in the dark blue region focus only on transforming already captured CO_2. The energies reported for these companies does not include the energy required to capture the CO_2. The energy reported for the electrolyzer systems assume 100% conversion efficiency of CO_2 which is not realistic, so there would be additional energy costs for a recirculating system.



Supplementary Figure 2: Schematic representation of the steps for various prototype systems designed to capture CO_2 and/or convert it to either concentrated and pressurized CO_2 or to a value-added product. The blue arrows represent prototype processes that capture and convert CO_2, grey arrows represent prototype processes that only focus on CO_2 conversion, and the pink arrow represents the process that we propose.

Section I: Energy Input Calculations for CO_2 Capture and Conversion Processes

A: Carbon Engineering

Carbon Engineering uses fans to contact air with a basic solution, thus dissolving CO_2 and transforming it into carbonate.[1] The carbonate reacts with $Ca(OH)_2$ to form $CaCO_3$, which is then heated to release pure CO_2 for compression and storage. Carbon Engineering reports that their process for capturing CO_2 from the air requires 8.81 GJ per 1.3-1.5 metric tons of pure and compressed CO_2 produced. Below we convert this value to kJ/mol CO_2 so that the value can be readily compared to other processes reported.

$$Energy = \frac{8.81\ GJ}{1.3 - 1.5\ t\ pure\ CO_2} \times \frac{1\ t\ pure\ CO_2}{1000kg} \times \frac{1kg}{1000g} \times \frac{44.01\ g}{1\ mol\ CO_2} \times \frac{1000000\ kJ}{1\ GJ} = \frac{259\ to\ 298\ kJ}{mol\ CO_2}$$

We would like to note that Carbon Engineering has now reported that they have also developed a process to make liquid fuels with their captured CO_2. They estimate the cost will be $1/L once the process is scaled up.[2] However, they do not report any details on how they do this, what specific fuel they synthesize, or the energy requirements of the process, so we will not discuss this process further.

B: CarbFix

Ragnheidardottier, E., et al.[3] reports that the power requirement for the CarbFix pilot plant is 200 kW and it stores 2099 metric tons of CO_2 annually. Below we use these values to convert to kJ/mol CO_2 so that the value can be readily compared to other processes reported.

$$Energy = \frac{200\ kJ}{s} \times \frac{3600\ sec}{1\ hr} \times \frac{24\ hrs}{1\ day} \times \frac{365\ days}{1\ yr} \times \frac{1\ yr}{2099\ tCO_2} \times \frac{1\ t\ CO_2}{1000kg} \times \frac{1kg}{1000g} \times \frac{44.01\ g}{1\ mol\ CO_2} = \frac{132\ kJ}{mol\ CO_2}$$

C: Carbon Recycling International

Kauw, M. et al.[4] report that the Carbon Recycling International 5M plant consumes 47.9 MJ/kg methanol. Below we convert this value to kJ/mol CO_2 so that the value can be readily compared to other processes reported.

$$Energy = \frac{47.9\ MJ}{kg\ methanol} \times \frac{1000\ kJ}{1\ MJ} \times \frac{1\ kg}{1000\ g} \times \frac{32.04\ g}{1\ mole\ methanol} \times \frac{1\ mol\ methanol}{1\ mole\ CO_2} = \frac{1535\ kJ}{mol\ CO_2}$$

D: Opus12

Opus 12 reports that their pilot device uses 5kW and produces 15kg of CO per day, and the input is concentrated CO_2.[5] We assume for these devices that the conversion percentage of CO_2 is 100%. Below we convert these values to kJ/mol CO_2 so that the value can be readily compared to other processes reported.

$$Energy = \frac{1\ day}{15000 g\ CO} \times \frac{24\ hrs}{1\ day} \times \frac{3600\ sec}{1\ hr} \times \frac{5\ kJ}{1\ sec} \times \frac{28.01\ g}{1\ mol\ CO} \times \frac{1\ mol\ CO}{1\ mole\ CO_2} = \frac{807\ kJ}{mol\ CO_2}$$

E: Dioxide Materials

Dioxide Materials provides information on the voltage at which to run their devices, the Faradaic efficiency, and the stability of the devices.[6,7] The electrolyzer that takes CO_2 to CO runs at 500mA/cm^2 at 3V full cell potential with a FE of 95%. The cathode is made of a Ag catalyst and the membrane is made of Sustanion, leading to a device stability of over 3000 hours.[7] The electrolyzer that takes CO_2 to formic acid runs at 160mA/cm^2 at 3.5V full cell potential with a FE of 90%. The cathode is made of an Sn nanoparticle catalyst, the membrane is made of Sustanion, and the counter is IrO_2.[6] We assume for these devices that the conversion percentage of CO_2 is 100%. We take this information and calculate the energy in kJ/mol CO_2.

For CO_2 to CO electrolyzer

$$Energy = \frac{UzF}{FE} = \frac{(3\ V)(2\ mole\ electrons)(96485\ \text{C mol}^{-1})}{.95} \times \frac{1\ kJ}{1000\ J} = \frac{609\ kJ}{mol\ CO_2}$$

For CO_2 to Formic Acid electrolyzer

$$Energy = \frac{UzF}{FE} = \frac{(3.5\ V)(2\ mole\ electrons)(96485\ \text{C mol}^{-1})}{.90} \times \frac{1\ kJ}{1000\ J} = \frac{750\ kJ}{mol\ CO_2}$$

F: Cement production

World Coal Association reports that it requires 200kg of coal to produce 1 metric ton of cement.[8] The higher heating value of coal is approximately 28.8-32.4 MJ/kg of coal according to the European Nuclear Society.[9] Carbon Cure can store 25 lbs of CO_2 per cubic yard of cement.[10] From these values we were able to calculate the amount of energy required per mol of CO_2 stored in the cement.

$$Energy \cong \frac{200\ kg\ coal}{1\ tonne\ cement} \times \frac{28.8\ to\ 32.4\ MJ}{1\ kg\ coal} \times \frac{1000\ kJ}{1\ MJ} \times \frac{1\ tonne}{1000\ kg} \times \frac{1\ kg}{1000\ g} \times \frac{3.15\ \ g\ cement}{1\ cm^3} \times \frac{764555 cm^3}{1\ yd^3} \times \frac{1\ yd^3}{25\ lb\ CO_2} \times \frac{1lb}{453.6\ g} \times \frac{44.01\ g\ CO_2}{1\ mol\ CO_2} = \frac{53{,}837\ to\ 60{,}567\ kJ}{mol\ CO_2}$$

G: Siemens and Evonik

Haas, T., et al.[11] report a system designed in collaboration between Siemens in Evonik.[11] This system uses a CO_2 electrolyzer to make syngas which is then fermented in the presence of bacteria. Depending on the type of bacteria, operating conditions, and ratio of CO to H_2, the fermenters either produce a 1:1 mixture of hexanol and butanol or a combination of acetate and ethanol. For the hexanol and butanol they report that this process requires 22kWh/kg of alcohol and then an additional 0.6 kWh/kg hexanol to

separate the alcohols. For the acetate and ethanol process they apply 4.94V over the whole CO_2 electrolyzer. The fermenter is put at 36°C.[11] We assume that the fermenter has a specific heat capacity of water to calculate the energy required to heat it. We then add the energy for the electrolyzer to the energy of the fermenter to obtain a final energy, this energy does not include the energy required to separate the products. In a practical system there would also be energy costs for pumps, feeding the bacteria, capturing the CO_2, etc. which we have not taken into account here.

For CO_2 to hexanol and butanol

$$Energy = \frac{22.6\ kWh}{kg\ alcohol} \times \frac{3600\ sec}{1\ hr} \times \frac{1\ kg\ alcohol}{1000\ g} \times \frac{.5\ (74.12 + 102.17)\ g}{1\ mol\ alcohol} = \frac{7{,}171\ kJ}{mol\ alcohol}$$

For CO_2 to acetate and ethanol

$$Energy = \frac{UzF}{FE} = \frac{(4.94\ V)(2\ mole\ electrons)(96485\ \mathrm{C\ mol^{-1}})}{1} \times \frac{1\ kJ}{1000\ J} = \frac{953\ kJ}{mol}$$

$$Q\ water = mc\Delta T = \left(2\ L\ H_2O \times \frac{1\ mole}{22.4L}\right) \times \frac{18.02\ g}{1\ mole\ H_2O} \times \frac{1\ kg}{1000\ g} \times \left(\frac{4.181\ kJ}{kg\ K}\right)(309 - 293K)$$
$$= \frac{0.11\ kJ}{mol\ H_2O}$$

H: Electrochaea[12]

For a BioCat 10 reaction the reported installed power is 220kW, the input of CO_2 is 500 Nm^3/h, the input of H_2 is 2000 Nm^3/h. The output is 500 Nm^3/h CH_4.[12]

$$Energy = \frac{220\ kJ}{1s} \times \frac{3600s}{1\ h} \times \frac{1h}{500\ Nm^3CO_2} \times \frac{1\ Nm^3}{1000L} \times \frac{22.4L}{1\ mol\ CO_2} = \frac{36\ kJ}{mol\ CO_2}$$

We assume use of an NEL H_2O electrolyzer to produce the H_2.[4]

$$Energy = \frac{52\ kWh}{1\ kg\ H_2} \times \frac{3600s}{1\ h} \times \frac{.002\ kg\ H_2}{1\ mol\ H_2} = \frac{374\ kJ}{mol\ H_2}$$

Section 2: Energy Input Calculations for Bicarbonate or Carbonate Feedstock Systems

A: Energy required to dissolve CO_2 in solutions of various alkalinity

Keith, D., et al.[13] report an air contactor that requires 61 kWh/tCO_2 for the fan which is 70% efficient and 21 kWh/tCO_2 for the fan which is 82% efficient.[13] In the air contactor described in this paper they have a basic solution comprised of 2M K^+, 0.45M CO_3^{2-} , 1.1M OH^-.[13] We have calculated the energy in kJ/mol CO_2 assuming this solution concentration and for a solution comprised of 2.24M K^+, 2.24M HCO_3^- , $10^{-4.78}$M OH^-.

Energy to dissolve CO_2 in solution to make carbonate

Solution: 2M K^+, 0.45M CO_3^{2-} , 1.1M OH^-

$$\frac{61\ kWh + 21\ kWh}{1\ tCO_2} \times \frac{3600\ sec}{1\ hr} \times \frac{1\ tCO_2}{1000\ kg} \times \frac{1\ kg}{1000\ g} \times \frac{44.01\ g\ CO_2}{1\ mol} = \frac{13\ kJ}{mol\ CO_2}$$

Energy to dissolve CO_2 in solution to make bicarbonate
Solution: 2.24M K^+, 2.24M HCO_3^- , $10^{-4.78}$M OH^-

$$\frac{61kWh}{1\ t\ CO_2} + \frac{21kWh}{1\ t\ CO_2} \times \frac{0.45M\ CO_3^{-2}}{2.24\ M\ HCO_3^-} = \frac{65\ kJ}{mol\ CO_2}$$

$$\frac{65\ kWh}{1\ t\ CO_2} \times \frac{3600\ sec}{1\ hr} \times \frac{1\ t\ CO_2}{1000\ kg} \times \frac{1\ kg}{1000\ g} \times \frac{44.01\ g\ CO_2}{1\ mol} = \frac{10\ kJ}{mol\ CO_2}$$

B: Bipolar membrane with Ag catalyst cathode and Ni foam anode
Sargent, E., et al.[14] reports a carbonate electrolyzer that uses a Ag catalyst cathode and a Ni foam anode separated by a bipolar membrane. The catholyte is a carbonate solution and the anolyte is a potassium hydroxide solution. The device is tested at various potentials; for our calculations we choose to look at when the applied a full cell potential of 3.8V, which gives the appropriate ratio of CO to H_2.[14]

$$Energy = \frac{UzF}{FE} = \frac{(3.8V)(2\ mole\ electrons)(96485.33212\ \text{C mol}^{-1})}{1} \times \frac{1\ kJ}{1000\ J} = \frac{733\ kJ}{mol\ CO_2}$$

This energy does not take into account the energy of the pumps or other practical considerations that would be needed for a functional system.

C: Bipolar membrane with Ag catalyst cathode and Ni anode
Li, T., et al.[15] reports an electrolyzer that uses a Ag catalyst at the cathode and a Ni anode to transform a solution of bicarbonate into syngas. When 3.5V is applied over the full cell the appropriate ratio of H_2 and CO are produced. Below we calculate the energy this corresponds to.[15]

$$Energy = \frac{UzF}{FE} = \frac{(3.5\ V)(2\ mole\ electrons)(96485\ \text{C mol}^{-1})}{1} \times \frac{1\ kJ}{1000\ J} = \frac{675\ kJ}{mol\ CO_2}$$

This energy does not take into account the energy of the pumps or other practical considerations that would be needed for a functional system.

D: Area required of electrolyzer, capture system, and solar cells
We calculate the area required for a plant able to process 1 metric ton of CO_2 per day (t-CO_2/day) and how much would area would be needed to convert the 37.1 gigatons of CO_2 emitted globally annually.[16] We also assume that the plant is operates continuously for 24 hours, all power needs are generated on site via solar energy, and that there is sufficient battery storage to power the capture and conversion

system continuously. We assume that the capture system is designed in the same way as Carbon Engineering's air contactor. They report that their air contactor processes 22 t-CO_2/m^2/yr and that the plant they describe in their report can capture 1 t-CO_2/day.[13] For the electrolyzer we assume that the metrics from the electrolyzer reported by Sargent, et al. – 200 mA/cm^2 at 3.8 V.[17] For the solar system we assume a 350 W solar panels with an area of 2.03 m^2.[18] The average capacity factor in the united states is approximately 25%.[19]

Calculate area of capture system to capture 1 t-CO_2 per day

$$Total\ Area = \frac{1\ t - CO_2}{day} \times \frac{365\ day}{1\ year} \times \frac{m^2 * year}{22\ t - CO_2} = 16.6\ m^2$$

Calculate area of electrolyzer to convert 1 t-CO_2 per day

$$Total\ Area = \frac{0.2\ C}{cm^2 * sec} \times \frac{10000\ cm^2}{1\ m^2} \times \frac{1\ mol\ CO_2}{3\ mol\ syngas} \times \frac{60\ sec}{1min} \times \frac{60\ min}{1\ hr} \times \frac{24\ hr}{1\ day} \times \frac{1\ electron}{1.6 * 10^{-19} C} \times \frac{1\ CO_2 molecule\ converted}{2\ electron} \times \frac{1\ mole\ CO_2}{6.022 * 10^{23} CO_2 molecule} \times \frac{.04401\ kg}{1\ mol\ CO_2} \times \frac{1\ ton}{1000\ kg} = \frac{2.36\ ton\ CO_2}{m^2 * day} = \frac{1\ ton\ CO_2}{0.38\ m^2 * day}$$

Calculate area of photovoltaic system needed to power plant that processes 1 t-CO_2 per day

$$Power\ density = \frac{350\ W}{2.03\ m^2} \times 0.25 \times 24\ hr = \frac{1.03\ kWh}{1\ m^2}$$

$$Total\ Area = \frac{746\ kJ}{mol\ CO_2} \times \frac{1\ mol\ CO_2}{.04401\ kg} \times \frac{1000\ kg}{1\ ton} \times \frac{0.0002778\ kWh}{1\ kJ} \times \frac{1\ m^2}{1.03\ \frac{kWh}{day} solar\ panel} = \frac{4571\ m^2}{tCO_2/day} \sim \frac{0.005\ km^2}{tCO_2/day}$$

Calculate area of whole system needed to process CO_2 emitted globally daily

$$Total\ area = \frac{37.1 * 10^9 tons\ CO_2}{1yr} \times \frac{1\ yr}{365\ days} \times \frac{4571\ m^2}{tCO_2/day} \times \frac{1\ km^2}{(1000\ m)^2} = 464{,}614\ km^2 \sim 460{,}000\ km^2$$

E: Energy required to make syngas from coal

Energy Technology Systems Analysis Programme reports that the process of synthesizing syngas from coal is roughly 74.7% efficient.[20] Syngas has roughly half of the energy density of natural gas. From this we can estimate the energy required to make syngas.

$$E = 0.5 \times \frac{33.4 - 82.7\ MJ}{1\ m^3\ natural\ gas} \times \frac{1 m^3}{1000L} \times \frac{22.4L}{1\ mol\ syngas} \times \frac{3\ mol\ syngas}{1\ mol\ CO} \times \frac{100}{74.7} = \frac{1.5 - 3.7\ MJ}{mol\ CO}$$

F: Energy required to make syngas from natural gas using steam reforming and the reverse water gas shift with CO_2 capture

For the process of steam reforming natural gas and then performing the reverse water gas shift to obtain the proper ratio of CO to H_2 there are many steps involved. Baltrusaitis, J. and W. Luyben[21] report that the energy for the preheater is 10.47 MW, vaporizer is 202.9 MW, steam methane reforming is 536.6 MW, the furnace for the reverse water gas shift is 121.2 MW, heat exchanger two is 219.8 MW, heat exchanger is 46 MW, the steam methane reforming cooler is 177.2 MW, the reboiler is 75.2 MW, the feed effluent heat exchanger is 53.2 MW, the condenser is 30.2 MW, the compressor is 9.83 MW, the intercoolers are 10.76 MW, and the stripper cooler is 40.86 MW. There are also some additional smaller energies that total 400MW. This system produces 15,013 kmol/h H_2, 7500 kmol/h CO, 271 kmol/h CH_4, and 94 kmol/h H_2O. From this we can calculate the energy needed to make the syngas.

$$\begin{aligned} Total\ power = {} & 10.47MW + 202.9MW + 536.6MW + 121.2MW + 46MW + 177.2MW + 75.2MW \\ & + 53.2\ MW + 30.2\ MW + 9.83\ MW + 10.76\ MW + 40.86MW + 400MW \\ & = 1{,}314.4\ MW \end{aligned}$$

$$E = \frac{1714.4\ MJ}{1s} \times \frac{60s}{1min} \times \frac{60\ min}{1hr} \times \frac{1hr}{7500\ kmol\ CO} \times \frac{1kmol}{1000mol} = \frac{0.8\ MJ}{mol\ CO}$$

G: Energy required to make syngas from natural gas using steam reforming and the reverse water gas shift

For the process of steam reforming natural gas and then performing the reverse water gas shift to obtain the proper ratio of CO to H_2 there are many steps involved. Baltrusaitis, J. and W. Luyben[21] report that the energy for the preheater is 10.47 MW, vaporizer is 202.9 MW, steam methane reforming is 536.6 MW, the furnace for the reverse water gas shift is 121.2 MW, heat exchanger two is 219.8 MW, heat exchanger 3 is 46 MW, compressor is 9.83MW, and the steam methane reforming cooler is 177.2 MW here are also some additional smaller energies that total 400MW. This system produces 15,013 kmol/h H_2, 7500 kmol/h CO, 272 kmol/h CH_4, and 75 kmol/h H_2O. From this we can calculate the energy needed to make the syngas.

$$\begin{aligned} Total\ power = {} & 10.47MW + 202.9MW + 536.6MW + 121.2MW + 46MW + 177.2MW \\ & + 9.83\ MW + 400MW = 1{,}504.2\ MW \end{aligned}$$

$$E = \frac{1314.4\ MJ}{1s} \times \frac{60s}{1min} \times \frac{60\ min}{1hr} \times \frac{1hr}{7500\ kmol\ CO} \times \frac{1kmol}{1000mol} = \frac{0.7\ MJ}{mol\ CO}$$

H: Pd-Pt cathode with Pt anode to reduce bicarbonate to formate

Kortlever, R., et al. reports an electrochemical cell that reduces bicarbonate to formate at low overpotentials using a Pd-Pt cathode and Pt anode. A potential of -0.4V vs the reversible hydrogen electrode (RHE) is applied to the cathode, which corresponds to ~90% faradaic efficiency for formate.[22] We assume a full cell potential of 2V, since the cell has some resistance and the anode is performing OER which has a standard potential of 1.23V. We have calculated the energy used by the cell below,

the calculation does not include the energy that would be required for pumps or other practical considerations.

$$Energy = \frac{UzF}{FE} = \frac{(2\ V)(2\ mole\ electrons)(96485\ \text{C mol}^{-1})}{.90} \times \frac{1\ kJ}{1000\ J} = \frac{429\ kJ}{mol\ CO_2}$$

H: Production of Sodium Hydroxide

The Office of Energy Efficiency and Renewable Energy of the U.S. Department of Energy report that when a zero-gap membrane chlor-alkali cell with an oxygen-depolarized cathode is used for the chlor-alkali process, sodium hydroxide can be produced for 2,500 kWh/ton.[23]

$$Energy = \frac{2{,}500\ kWh}{1\ ton\ NaOH} * \frac{3600\ kJ}{1\ kWh} \times \frac{1\ ton}{1000\ kg} \times \frac{1\ kg}{1000\ g} \times \frac{39.997\ g\ NaPH}{1\ mol\ NaOH} = \frac{360\ kJ}{mol\ NaOH}$$

Section 3: CO_2 Electrolyzer Conversion Efficiencies

For all calculations in this section we assume that the CO_2 is at standard temperature and pressure.

A: Gewirth, A., et al CO_2 to electrolyzer[24]

$$Mols\ of\ CO_2\ per\ second = \left(\frac{7\ ml\ CO_2}{1\ min}\right)\left(\frac{1\ min}{60s}\right)\left(\frac{22{,}400\ ml\ CO_2}{1\ mol\ CO_2}\right) = \frac{5.2 * 10^{-6}\ mol\ CO_2}{1s}$$

$$Mols\ of\ ethylene\ per\ second = \left(\frac{.17\ C}{1s}\right)\left(\frac{1\ mol\ e-}{96485\ C}\right)\left(\frac{1\ mol\ ethylene}{12\ mol\ e-}\right) = \frac{1.5 * 10^{-10}\ mol\ CO}{1s}$$

$$Mols\ of\ ethanol\ per\ second = \left(\frac{.09\ C}{1s}\right)\left(\frac{1\ mol\ e-}{96485\ C}\right)\left(\frac{1\ mol\ ethanol}{12\ mol\ e-}\right) = \frac{7.8 * 10^{-11}\ mol\ CO}{1s}$$

$$Conversion\ Percentage = \frac{2.2 * 10^{-10}\ mol\ C2}{1s} * \frac{1s}{5.2 * 10^{-6}\ mol\ CO_2} = 0.004\%$$

B: Siemens and Evonik CO_2 electrolyzer[11]

$$Mols\ of\ CO_2\ per\ second = \left(\frac{90\ ml\ CO_2}{1\ min}\right)\left(\frac{1\ min}{60s}\right)\left(\frac{22{,}400\ ml\ CO_2}{1\ mol\ CO_2}\right) = \frac{6.7 * 10^{-5}\ mol\ CO_2}{1s}$$

$$Mols\ of\ Formate\ per\ second = \left(\frac{.3\ C}{1s}\right)\left(\frac{1\ mol\ e-}{96485\ C}\right)\left(\frac{1\ mol\ CO}{2\ mol\ e-}\right) * .7 = \frac{1.1 * 10^{-6}\ mol\ CO}{1s}$$

$$Conversion\ Percentage = \frac{1.1 * 10^{-6}\ mol\ CO}{1s} * \frac{1s}{6.7 * 10^{-5}\ mol\ CO_2} = 1.6\%$$

C: Sargent, E., et al CO_2 electrolyzer[25]

$$Mols\ of\ CO_2\ per\ second = \left(\frac{30\ ml\ CO_2}{1\ min}\right)\left(\frac{1\ min}{60s}\right)\left(\frac{22{,}400\ ml\ CO_2}{1\ mol\ CO_2}\right) = \frac{2.2 * 10^{-5}\ mol\ CO_2}{1s}$$

$$Mols\ of\ Acetic\ acid\ per\ second = \left(\frac{.75\ C}{1s}\right)\left(\frac{1\ mol\ e-}{96485\ C}\right)\left(\frac{1\ mol\ acetic\ acid}{8\ mol\ e-}\right) * .05$$
$$= \frac{4.8 * 10^{-8}\ mol\ acetic\ acid}{1s}$$
$$Mols\ of\ ethylene\ per\ second = \left(\frac{.75\ C}{1s}\right)\left(\frac{1\ mol\ e-}{96485\ C}\right)\left(\frac{1\ mol\ ethylene}{12\ mol\ e-}\right) * .65$$
$$= \frac{4.2 * 10^{-7}\ mol\ CO}{1s}$$

$$Mols\ of\ ethanol\ per\ second = \left(\frac{.75\ C}{1s}\right)\left(\frac{1\ mol\ e-}{96485\ C}\right)\left(\frac{1\ mol\ ethanol}{12\ mol\ e-}\right) * .1 = \frac{6.4 * 10^{-8}\ mol\ CO}{1s}$$

$$Conversion\ Percentage = \frac{5.3 * 10^{-7}\ mol\ C2}{1s} * \frac{1s}{2.2 * 10^{-5}\ mol\ CO_2} = 2.4\%$$

D: Kenis, P., et al CO_2 electrolyzer[26]

$$Mols\ of\ CO_2\ per\ second = \left(\frac{7\ ml\ CO_2}{1\ min}\right)\left(\frac{1\ min}{60s}\right)\left(\frac{22{,}400\ ml\ CO_2}{1\ mol\ CO_2}\right) = \frac{5.2 * 10^{-6}\ mol\ CO_2}{1s}$$

$$Mols\ of\ CO\ per\ second = \left(\frac{.275\ C}{1s}\right)\left(\frac{1\ mol\ e-}{96485\ C}\right)\left(\frac{1\ mol\ CO}{2\ mol\ e-}\right) *= \frac{1.4 * 10^{-6}\ mol\ CO}{1s}$$

$$Conversion\ Percentage = \frac{5.3 * 10^{-7}\ mol\ CO}{1s} * \frac{1s}{2.2 * 10^{-5}\ mol\ CO_2} = 27.3\%$$

E: Kenis, P., et al CO_2 electrolyzer[27]

$$Mols\ of\ CO_2\ per\ second = \left(\frac{7\ ml\ CO_2}{1\ min}\right)\left(\frac{1\ min}{60s}\right)\left(\frac{22{,}400\ ml\ CO_2}{1\ mol\ CO_2}\right) = \frac{5.2 * 10^{-6}\ mol\ CO_2}{1s}$$

$$Mols\ of\ CO\ per\ second = \left(\frac{.375\ C}{1s}\right)\left(\frac{1\ mol\ e-}{96485\ C}\right)\left(\frac{1\ mol\ CO}{2\ mol\ e-}\right) = \frac{1.8 * 10^{-6}\ mol\ CO}{1s}$$

$$Conversion\ Percentage = \frac{5.3 * 10^{-7}\ mol\ CO}{1s} * \frac{1s}{2.2 * 10^{-5}\ mol\ CO_2} = 34.8\%$$

F: Xuan, J., et al CO_2 electrolyzer[28]

$$Mols\ of\ CO_2\ per\ second = \left(\frac{50\ ml\ CO_2}{1\ min}\right)\left(\frac{1\ min}{60s}\right)\left(\frac{22{,}400\ ml\ CO_2}{1\ mol\ CO_2}\right) = \frac{3.7 * 10^{-5}\ mol\ CO_2}{1s}$$

$$Mols\ of\ formate\ per\ second = \left(\frac{.350\ C}{1s}\right)\left(\frac{1\ mol\ e-}{96485\ C}\right)\left(\frac{1\ mol\ HCOO^-}{2\ mol\ e-}\right) = \frac{1.8 * 10^{-6}\ mol\ HCOO^-}{1s}$$

$$Conversion\ Percentage = \frac{1.8 * 10^{-6}\ mol\ HCOO^-}{1s} * \frac{1s}{3.7 * 10^{-5}\ mol\ CO_2} = 4.9\%$$

G: Lv, J. J., et al CO_2 electrolyzer[29]

$$Mols\ of\ CO_2\ per\ second = \left(\frac{10\ ml\ CO_2}{1\ min}\right)\left(\frac{1\ min}{60s}\right)\left(\frac{22{,}400\ ml\ CO_2}{1\ mol\ CO_2}\right) = \frac{7.4 * 10^{-6}\ mol\ CO_2}{1s}$$

$$Mols\ of\ ethylene\ per\ second = \left(\frac{.255\ C}{1s}\right)\left(\frac{1\ mol\ e-}{96485\ C}\right)\left(\frac{1\ mol\ C_2H_4}{12\ mol\ e-}\right) = \frac{2.2 * 10^{-7}\ mol\ C_2H_4}{1s}$$

$$Conversion\ Percentage = \frac{2.2 * 10^{-7}\ mol\ C_2H_4}{1s} * \frac{1s}{7.4 * 10^{-6}\ mol\ CO_2} = 2.9\%$$

H: Verma, S., et al CO_2 electrolyzer[30]

$$Mols\ of\ CO_2\ per\ second = \left(\frac{10\ ml\ CO_2}{1\ min}\right)\left(\frac{1\ min}{60s}\right)\left(\frac{22{,}400\ ml\ CO_2}{1\ mol\ CO_2}\right) = \frac{1.3 * 10^{-5}\ mol\ CO_2}{1s}$$

$$Mols\ of\ CO\ per\ second = \left(\frac{.255\ C}{1s}\right)\left(\frac{1\ mol\ e-}{96485\ C}\right)\left(\frac{1\ mol\ CO}{2\ mol\ e-}\right) = \frac{8.3 * 10^{-7}\ mol\ CO}{1s}$$

$$Conversion\ Percentage = \frac{2.2 * 10^{-7}\ mol\ CO}{1s} * \frac{1s}{7.4 * 10^{-6}\ mol\ CO_2} = 6.6\%$$

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